

J/ψ and ψ' total cross sections and formation times from data for charmonium suppression in pA collisions

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Abstract

The recent data for E866 on the x_F dependence for charmonium suppression in pA collisions at 800 GeV are analyzed using a time- and energy-dependent preformed charmonium absorption cross section $\sigma_{\text{abs}}^{\psi}(\tau, \sqrt{s_{\psi N}})$. For $\sqrt{s} = 10$ GeV the initially ($\tau = 0$) produced premeson has an absorption cross section of $\sigma_{\text{pr}} \simeq 3$ mb. At the same energy but for $\tau \rightarrow \infty$ one deduces for the total cross sections $\sigma_{\text{tot}}^{J/\psi N} = (2.8 \pm 0.3)$ mb, $\sigma_{\text{tot}}^{\psi' N} = (10.5 \pm 3.6)$ mb. The data are compatible with a formation time $\tau_{1/2} = 0.6$ fm/ c .

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The formation of a charmonium meson J/ψ or ψ' from the originally produced $c\bar{c}$ pair via gluon fusion is a point of discussion and disagreement in the community which investigates the charmonium suppression in nucleus-nucleus collisions [1–6]. What is the nature (color, size) of the premeson when it travels through nuclear matter? How long does it take to be a fully developed J/ψ or ψ' ? Are the formation times different for J/ψ and ψ' , the ψ' being considerably larger than the J/ψ ? What are the total cross sections $\sigma_{tot}^{J/\psi N}$, $\sigma_{tot}^{\psi' N}$, for the fully developed charmonia on a nucleon? These questions can be possibly answered using the recent and still preliminary data of the E866 collaboration [7]. The analysis will be given in this paper. Since the data are still preliminary, this letter stresses the method of the analysis, while the numerical results may still undergo certain modifications.

In an experiment $pA \longrightarrow \psi X$ at 800 GeV, where ψ stands for J/ψ and ψ' , the suppression

$$S_\psi(x_F) = \frac{d\sigma(pA \longrightarrow J/\psi X)}{Ad\sigma(pN \longrightarrow J/\psi X)} \quad (1)$$

has been measured as a function of x_F for the produced ψ in the range $x_F \gtrsim -0.1$. We will concentrate in this paper on the interval $-0.1 \lesssim x_F \lesssim 0.25$ where formation time effects are expected to be of particular importance and where effects of the production time (coherence time) can be neglected. The effects of the formation time are determined by the Lorentz factor $\gamma(x_F)$ of the charmonium with respect to the target nucleus. In the experiment pA at 800 GeV, γ varies between a value of 7 at $x_F = -0.15$ and a value of 47 at $x_F = +0.15$. For a hypothetical value of the charmonium formation time $\tau_f = 0.5$ fm/c in the c.m.s. and for a premeson which is produced in the middle of a nucleus with radius $R_A = 6$ fm, a ψ observed with $x_F = -0.15$ is essentially fully developed inside the nucleus and absorbed with the asymptotic total cross section $\sigma_{tot}^{\psi N}$, while for $x_F = 0.15$ the ψ traverses the nucleus in the form of a premeson.

On the other hand, the coherence time t_c of charmonium production, which is the quantum-mechanical uncertainty in the time of production of the premeson is quite short in the interval of consideration. In the light-cone approach t_c can be treated as the lifetime of a fluctuation containing the $c\bar{c}$. It is given by the energy denominator corresponding to

such a fluctuation,

$$t_c = \frac{2 E_G}{M^2} , \quad (2)$$

where M^2 is the effective mass of the fluctuation. We assume here that the $\bar{c}c$ pair is produced via gluon-gluon fusion accompanied by gluon radiation which is needed in order to end up with a color neutral $\bar{c}c$ pair. It would be incorrect to say that the gluon is radiated *after* its interaction with the target. As usual with bremsstrahlung it takes place both *before* and *after* the interaction. This is a quantum-mechanical uncertainty. In the light-cone approach t_c corresponds to the lifetime of the whole fluctuation $G \rightarrow \bar{c}cG$. This is why Eq. (2) contains the gluon energy E_G in the numerator and in the denominator the effective mass of the $\bar{q}qG$ [8],

$$M^2 = \frac{k_T^2}{\alpha(1-\alpha)} + \frac{M_{\bar{c}c}^2}{1-\alpha} . \quad (3)$$

Here k_T and α are the transverse momentum and the fraction of the initial light-cone momentum carried by the radiated gluon, respectively. $M_{\bar{c}c}$ is the effective mass of the $\bar{c}c$ pair which we assume to be of the order of the charmonium mass. It is important to note that k_T cannot be small since the radiated gluon has to resolve the inner structure of the $\bar{c}c$ pair in order to make it colorless. Therefore, it should be larger than the inverse $\bar{c}c$ separation, $k_T > 1/r_{\bar{c}c}^{\bar{c}c} \sim m_c$. At the same time, the fraction α should not be large, otherwise it will produce a shift in the initial gluon momentum, which falls off steeply like $(1-x_1)^5$, resulting in a strong suppression. A detailed calculation leads to values $t_c = 0.25 \text{ fm}/c$ at $x_F = -0.15$ and $t_c = 4.1 \text{ fm}/c$ at $x_F = 0.15$ in the lab system and $\tau_c = 0.04 \text{ fm}/c$ and $\tau_c = 0.08 \text{ fm}/c$ in the pmeson c.m.s., respectively. Indeed we will see $\tau_c \ll \tau_f$. For values of $0.3 < x_F < 0.8$ one has $t_c > R$ and the formation time concept becomes doubtful, another mechanism seems to be responsible for the observed suppression.

In the x_F interval $[-0.1, 0.25]$ we model the suppression by assuming that the pmeson is created instantaneously and is absorbed according to a time and energy dependent effective absorption cross section $\sigma_{\text{abs}}^{\psi N}(\tau, \sqrt{s_{\psi N}})$ for an experiment, in which a charmonium ψ is

observed. (The effects of the decays $\chi_c \rightarrow J/\psi$ and $\psi' \rightarrow J/\psi$ will be discussed later.) The classical expression

$$S_\psi(x_F) = \frac{1}{A} \int d^2b \int_{-\infty}^{\infty} dz \rho_A(b, z) \exp \left\{ - \int_z^{\infty} dz' \rho_A(b, z') \sigma_{\text{abs}}^{\psi} \left(\frac{z' - z}{\gamma(x_F)}, \sqrt{s_{\psi N}(x_F)} \right) \right\}, \quad (4)$$

is used with the nuclear density distribution $\rho_A(b, z)$ normalized to A . This expression is an approximation to exact solutions for the evolution of a wave packet with charmonium quantum numbers propagating through a medium treated in the quark [4] or in hadronic [10] representations (see also below). We believe that Eq. (4) is more intuitive and easier to use than the exact ones. Our aim is to determine the dependence of $\sigma_{\text{abs}}^{J/\psi}(\tau, \sqrt{s_{\psi N}})$ and $\sigma_{\text{abs}}^{\psi'}(\tau, \sqrt{s_{\psi N}})$ from a fit of Eq. (4) to the E866 data.

We use the following expression for $\sigma_{\text{abs}}^{\psi N}(\tau, \sqrt{s_{\psi N}})$ with two adjustable parameters Σ_0 and Σ_∞ which correspond to the effective absorptive cross section at short and long times, respectively,

$$\sigma_{\text{abs}}^{\psi N}(\tau, \sqrt{s_{\psi N}}) = [\Sigma_\infty + (\Sigma_\infty - \Sigma_0) \cos(\Delta M \tau)] \left(\frac{\sqrt{s_{\psi N}}}{10 \text{GeV}} \right)^\lambda. \quad (5)$$

The dependence on the energy $\sqrt{s_{\psi N}}$ is deduced from photoproduction experiments ($\gamma p \rightarrow J/\psi p$) with $\lambda = 0.4$ [11]. The form of the dependence on the time τ is derived within the following quantum mechanical model of two coupled channels for the evolution of a color neutral $c\bar{c}$ pair [5]¹: The time dependent premeson state $|c\bar{c}(\tau)\rangle$ with the quantum numbers of J/ψ and ψ' can be expanded in a complete set of hadronic states of which we keep only the lowest two ones, J/ψ and ψ' , and we may use spinor representation: We denote by

$$|c\bar{c}(0)\rangle = \frac{1}{\sqrt{1+R^2}} \begin{pmatrix} J/\psi \\ R \psi' \end{pmatrix} \quad (6)$$

the initially produced superposition of the J/ψ and ψ' . The $|\bar{c}c\rangle$ wave packet in an interacting environment is described by the equation,

¹ We assume that the state $|\bar{c}c\rangle$ includes all the Fock components with additional gluons and sea quarks, $|\bar{c}c\rangle = |\bar{c}c\rangle_0 + |\bar{c}cG\rangle + \dots$

$$i \frac{d \bar{c}c(\tau)}{d\tau} = \left(\hat{Q} - \frac{i}{2} \rho_A(b, z = \tau\gamma) \gamma \hat{T} \right) |\bar{q}q(\tau)\rangle, \quad (7)$$

with

$$\hat{Q} = \begin{pmatrix} M_{J/\psi} & 0 \\ 0 & M_{\psi'} \end{pmatrix}, \quad \hat{T} = \begin{pmatrix} \sigma_{00} & \sigma_{01} \\ \sigma_{10} & \sigma_{11} \end{pmatrix} \quad (8)$$

where \hat{Q} is the mass matrix and \hat{T} is the interaction amplitude operator containing diagonal and off-diagonal amplitudes, $\sigma_{00} = \langle J/\psi | \hat{\sigma} | J/\psi \rangle$, $\sigma_{01} = \langle J/\psi | \hat{\sigma} | \psi' \rangle$, *etc.* [10].

For a $|c\bar{c}\rangle$ created at the point (b, z) in the nucleus and observed asymptotically as a ψ one has the transition probability

$$W_\psi(b, z) = \frac{|\langle \psi | c\bar{c}(\frac{z'-z}{\gamma}) \rangle|^2}{|\langle \psi | c\bar{c}(0) \rangle|^2}, \quad (9)$$

where $|c\bar{c}(\frac{z'-z}{\gamma})\rangle$ (it depends also on b) is the solution of Eq. (7) with the initial state (6) at the point with coordinates (b, z) .

Expanding expression (9) in ρ_A up to the first order we get,

$$\begin{aligned} W_{J/\psi} &= 1 - \int_z^\infty dz' \rho_A(b, z') \left[\sigma_{00} + R \sigma_{10} \cos \left(\Delta M \frac{z' - z}{\gamma} \right) \right] \\ W_{\psi'} &= 1 - \int_z^\infty dz' \rho_A(b, z') \left[\sigma_{11} + \frac{1}{R} \sigma_{01} \cos \left(\Delta M \frac{z' - z}{\gamma} \right) \right] \end{aligned} \quad (10)$$

with $\Delta M = M_{\psi'} - M_{J/\psi}$.

The expressions in square brackets in Eq. (10) are the time dependent effective absorption cross sections and are of the form assumed in Eq. (5). These effective cross sections may be positive and negative. In the latter case one observes an enhanced production if one uses a nuclear target [4].

We have calculated the suppression function $S_\psi(x_F)$ in Eq. (4) for Tungsten $A = 182$ and Beryllium $A = 9$ with a uniform density, and $R = r_0 A^{1/3}$ with $r_0 = 1.14$ fm. The two parameters Σ_0 , and Σ_∞ for each species of charmonium have been determined by fitting Eq. (1) to the data of J/ψ and ψ' suppression, respectively. We have used MINUIT-Hesse from CERNLIB. Fig. 1 shows the fits. The numerical values of the parameters together with their errors and the values χ_{dof}^2 as given by the fit routine are displayed in Table 1.

In the following discussion of the results we always take $\sqrt{s_{\psi N}} = 10$ GeV.

For $\tau \rightarrow \infty$, the oscillating term in the parameterizations Eq. (5) does not contribute in the integral for the suppression. This is the situation of the fully developed charmonium and the parameter Σ_∞ can be identified with the total cross sections,

$$\sigma_{tot}^{“J/\psi”N} = (5.0 \pm 0.4) \text{ mb}, \quad \sigma_{tot}^{\psi'N} = (10.5 \pm 3.6) \text{ mb}. \quad (11)$$

We have set J/ψ in quotation marks, since the total cross section $\sigma_{tot}^{“J/\psi”N}$ is the one for a situation, where the observed J/ψ originates with probability $p_1 \simeq 0.6$ from directly formed J/ψ , and probability $p_2 \simeq 0.3$ and $p_3 \simeq 0.1$ from the decay of χ_c and ψ' , respectively. Thus the total effective absorption cross section seen in the “ J/ψ ” channel is a superposition of the contributions of J/ψ , χ_c , and ψ' . If we correct for this effect, assuming that total cross sections are proportional to $\langle r^2 \rangle$ one has

$$\begin{aligned} \sigma_{tot}^{J/\psi N} &= \sigma_{tot}^{“J/\psi”N} \left[p_1 + \frac{p_2 \langle r^2 \rangle_\chi + p_3 \langle r^2 \rangle_{\psi'}}{\langle r^2 \rangle_{J/\psi}} \right]^{-1} \\ &= 2.8 \pm 0.3 \text{ mb} , \end{aligned} \quad (12)$$

where we have used $\langle r^2 \rangle_{J/\psi}^{1/2} = 0.42$ fm, $\langle r^2 \rangle_\chi^{1/2} = 0.67$ fm, $\langle r^2 \rangle_{\psi'}^{1/2} = 0.85$ fm [12]. The value in Eq. (12) can be compared with $\sigma_{tot}^{J/\psi N} = (3.5 \pm 0.7)$ mb obtained from an analysis of photoproduction data $\gamma p \rightarrow J/\psi p$ using the modified vector dominance model [11].

The ratio of the values from Eqs. (11) and (12) gives

$$\frac{\sigma_{tot}^{\psi'N}}{\sigma_{tot}^{J/\psi N}} = 3.8 \pm 1.3, \quad (13)$$

which is close to the value derived from ψ' photoproduction [11] and coincides with the prediction based on the ratio of the corresponding values of $\langle r^2 \rangle$ which leads to 4 when the calculations by Buchmüller [12] are used.

Next we discuss the size of the absorption cross sections for a premeson directly after creation, *i.e.* at $\tau = 0$. Then according to Eq. (5), the cross sections are related to Σ_0 . Using the data from Table 1 we have

$$\sigma_{\text{pr}} = \begin{cases} 2.7 \pm 0.1 \text{ mb} & J/\psi \text{ observed} \\ 3.8 \pm 0.6 \text{ mb} & \psi' \text{ observed} . \end{cases}$$

The two values are rather small compared to the asymptotic cross sections, supporting the idea that the initial $c\bar{c}$ system is rather small. The values in Eq. (14) are equal within the large error bars, although there is no compelling reason why they should be the same. For instance, one of the origins for a difference is the admixture of the χ_c -states in the J/ψ channel, which at $\tau \rightarrow 0$ cannot be corrected for easily since the $\langle r^2 \rangle$ law is not applicable.

Within the two channel model the time dependence of the effective absorption cross section, Eq. (5) is given by the characteristic time $1/\Delta M = 0.3 \text{ fm}/c$, where ΔM is the mass difference between the states J/ψ and ψ' . We have not varied this characteristic time since only few data points are available with rather larger error bars. However, since the parameters Σ_0 and Σ_∞ deduced from the experiment yield a consistent picture and values of $\chi^2_{dof} < 1$, the time dependence derived from the two channel model may not be unreasonable. The oscillating dependence of the cross section in Eq. (5) makes the physical interpretation of the characteristic time somewhat difficult. Since the cross sections always appear under the integral we may define a formation time $\tau_{1/2}$ by the requirement that the contribution of the oscillating term is reduced by 50%, *i.e.* we define $\tau_{1/2}$ by

$$\frac{1}{\tau_{1/2}} \int_0^{\tau_{1/2}} d\tau \cos \Delta M \tau = \frac{1}{2}, \quad (14)$$

which happens at $\tau_{1/2} = 1.9/\Delta M = 0.6 \text{ fm}/c$.

The previous analysis is based exclusively on the data of E866 and has yielded the time and energy dependent absorption cross sections $\sigma_{\text{abs}}^{\psi N}(\tau, \sqrt{s_{\psi N}})$ parametrized as in Eq. (5). We have checked, whether our results are consistent with other data, for instance, measurements of J/ψ suppression at 200 GeV (NA3) and ratios of ψ' to J/ψ suppression at 450 and 200 GeV (NA38/50). In the experiment of NA3 [14], where Pt and ^2H have been the targets, only four data points are available for $x_F \lesssim 0.4$, where formation time effects are supposed to be the dominant mechanism. We have varied only Σ_∞ , while setting Σ_0 at the value derived from the 800 GeV data. The results from the fit are also given in the Table 1 and agree with the results from E866.

Furthermore, we have used the absorption cross sections as deduced from E866 to calcu-

late the ratio of $\psi'/J/\psi$ production on nuclear targets which has been measured by NA38 and NA50 for several nuclei and energies of 200 and 450 GeV. Results are shown in Fig. 2. Within the uncertainties induced by error bars of the fitted parameters, the data on $\psi'/J/\psi$ suppression can be understood with the time dependent absorption cross section.

We summarize: The data of the E866 experiment for the x_F dependence of the J/ψ and ψ' suppressions ($-0.1 \leq x_F \leq 0.25$) have been analyzed with the hypothesis that the variation is entirely due to a time- and energy-dependent effective absorption cross section for a premeson which evolves in time during its passage through the nucleus. The analysis is based on a set of hypotheses and approximations which we list, but whose accuracies cannot be estimated:

- We assume that formation time effects dominate the x_F -dependence of nuclear suppression for $x_F \lesssim 0.25$ where the coherence time is rather short.
- We assume that the formation times for J/ψ and ψ' are equal. It is frequently assumed based on the picture of classical expansion that the ψ' needs longer time to form than the J/ψ because of its larger radius. This might be not true in quantum mechanics. For instance, for the oscillator potential the formation time is size independent (the period of oscillation of a pendulum is independent of the amplitude).
- The energy and time dependence of the absorption cross section factorizes $\sigma_{\text{abs}}(\tau, \sqrt{s}) = \sigma(\tau)(s/s_0)^\lambda$. The dependence of λ on the transverse $\bar{c}c$ separation is rather weak [15] and we fix it at $\lambda = 0.2$ which follows from J/Ψ photoproduction data.
- We have assumed one exponential in each channel when calculating the suppression function $S_\psi(x_F)$, although the situation is more complicated (coupled system of J/ψ and ψ' , contribution of χ_c , *etc.*) as is suggested by the evolution equation (7) for two coupled channels and the exact solution (9) which can be found in [10].

Despite these uncertainties, the analysis has provided a coherent description of the data from

E866, NA3 and NA38/50. We have extracted values for $\sigma_{\text{tot}}^{J/\psi N}$ and $\sigma_{\text{tot}}^{\psi' N}$, which agree with values extracted from photoproduction experiments and follow the systematics of values of hN total cross sections σ_{tot}^{hN} as a function of $\langle r^2 \rangle_h$. For small times, $\tau \rightarrow 0$, one finds smaller absorption cross sections, as expected, if the premeson is small in size. No statement can be made about the color structure. Although we have not varied the formation time, the fit is very good for the formation time $\tau_{1/2} \simeq 0.6 \text{ fm}/c$ derived from the two channel model.

After our analysis was complete Ref. [16] has appeared in which the same data are analysed as in this work but with a quite different approach. It covers the whole range of x_F , and treats the evolution of the $\bar{c}c$ pair purely classically.

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FIGURES

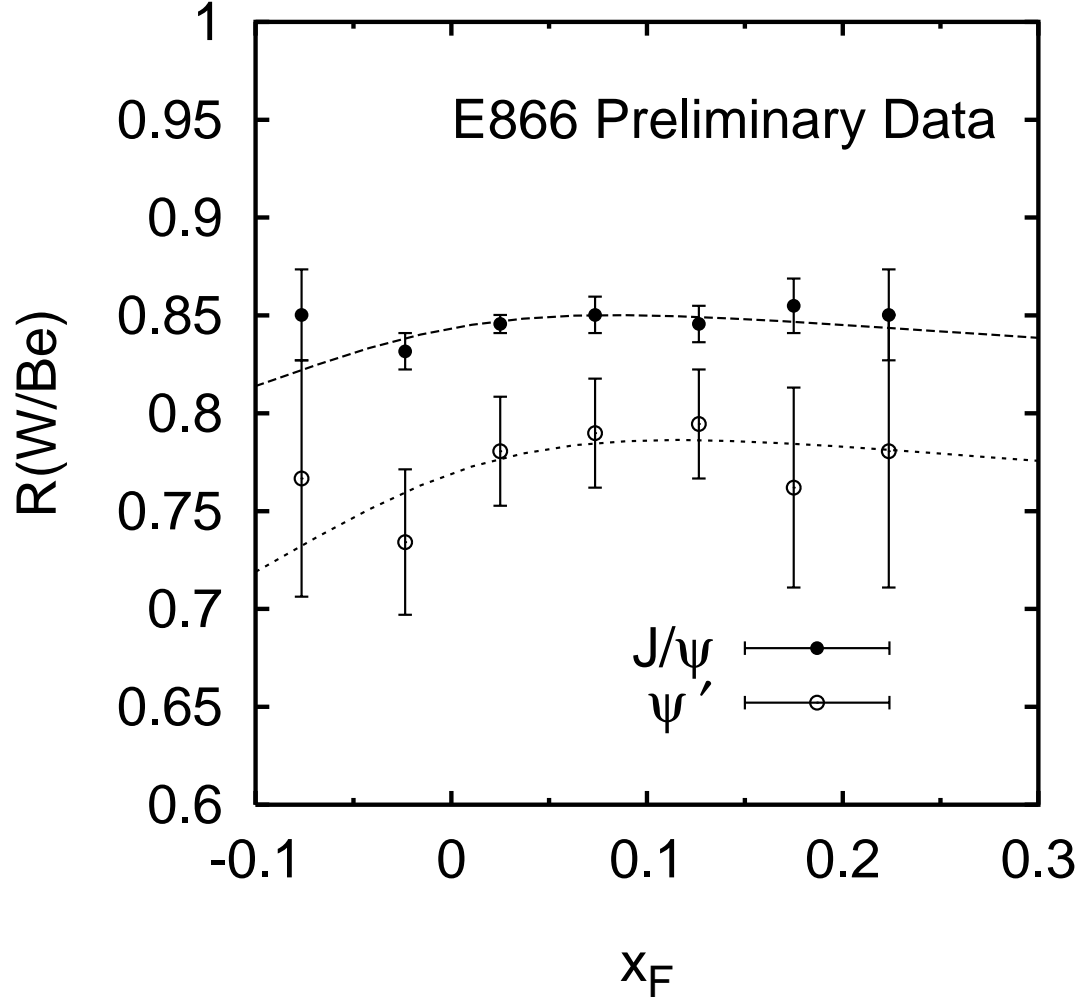


FIG. 1. Data from E866 for the ratio of charmonium production in pW and pBe collisions together with our best fits using Eq. (4).

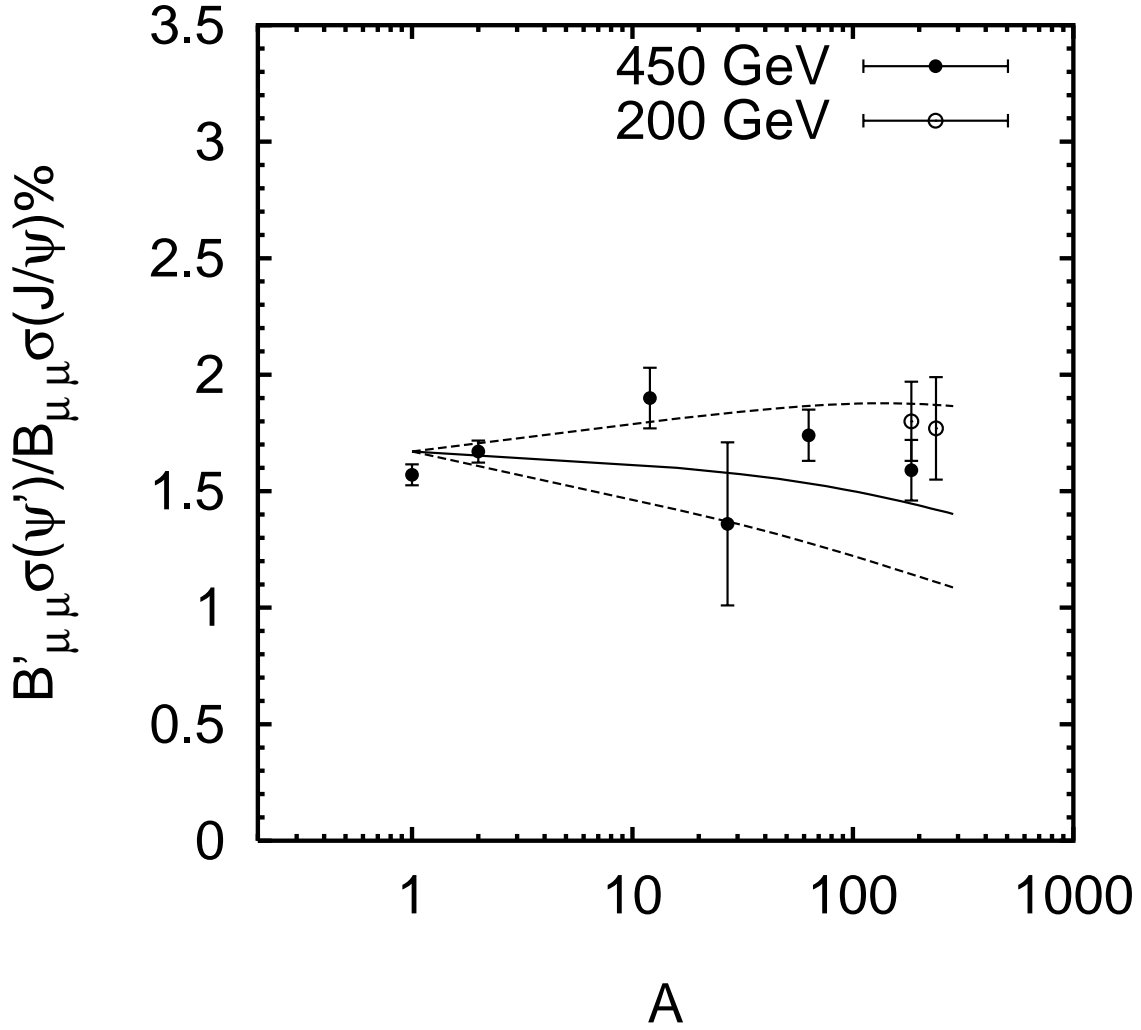


FIG. 2. Results for the ratio $B'_{\mu\mu}\sigma(\psi')/B_{\mu\mu}\sigma(J/\psi)$ calculated from fitted parameters in Table 1 are compared with pA data at 200 and 450 GeV (data from NA51 and NA38). The solid curve corresponds to the calculation with parameters at their central values, while the upper and lower curves characterize the uncertainties induced by the error bars of the fitted parameters.

TABLES

(ψ)	(exp.)	$\Sigma_\infty[\text{mb}]$	$\Sigma_0[\text{mb}]$	χ^2_{dof}
J/ψ	(E866)	5.0 ± 0.4	2.7 ± 0.1	0.84
ψ'	(E866)	10.5 ± 3.6	3.8 ± 0.6	0.28
J/ψ	(NA3)	6.8 ± 1.7	[2.7]	1.6

TABLE I. Values for the parameters Σ_∞ and Σ_0 in the parametrization of the absorption cross section Eq. (5) as obtained from the least square fit to the data. For the NA3 experiment only the parameter Σ_∞ has been fitted, while the values of Σ_0 has been set at 2.7.